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A Review of Battle Damage Prediction and Vulnerability Reduction Methods

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ABSTRACT

This report provides a literature review of the area of battle damage prediction and vulnerability reduction methods in the land and maritime domains and will provide input into the strategic planning process for Maritime Platforms Division's (MPD) long range research program.

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Executive Summary

Maritime Platforms Division (MPD) has a long and well established expertise in the areas of explosive blast and ballistics effects on Australian Defence Force (ADF) platforms. This expertise allows DSTO to provide advice and guidance for operations and the force-in-being; provide science and technology support to acquisitions; support Defence industry development and position the Australian Defence Force to exploit the latest developments and adapt to changes in the conduct of war.

The complex nature of the conflict environment means that Defence must be predictive and reactive in nature, always trying to position our forces in the best possible way to defeat the opposition. This report highlights current ADF operations, and provides the context in which research in platform vulnerability and battle damage prediction is essential to maintain ADF's war fighting capability.

This report provides a range of armour and other vulnerability reduction measures which are currently being developed. The wide range of material and structural solutions to mitigate the damage from weapons effects is a result of the wide range of platforms, environmental conditions and threats being defeated. The appropriate development and selection of these solutions highlights the need for well trained technologists in the terminal effects field.

The report also reinforces the development of the Defence Materials Technology Centre (DMTC) in 2008 to provide the basic knowledge in the area of materials development for armour applications. It is essential that DSTO continues to align the focus of materials development with the current environmental and threat conditions within which the ADF operates. This is further strengthened by DSTO's domestic and international interactions under cooperative agreements.

The link between the development of simulation and modelling tools and the development of vulnerability reduction measures must be maintained, along with a fundamental understanding of the physical processes involved, in order to accurately predict potential battle damage.

This report highlights the following important areas of study:

1. Development of lightweight armour and applique armour solutions to defeat a range of weapons. Both land and maritime platforms have tight weight and cost constraints.

2. Continued development and understanding of the protective properties of new materials such as explosion resistant coatings (ERC). Platform manufacturers are currently offering ERC materials to various projects, however the basic performance parameters of existing materials are not known, nor are these materials optimised.

3. Development of much lighter, long life transparent armour which is able to defeat a range of fragmenting and penetrator threats, together with appropriate optical and non-ballistic properties such as environmental durability.

4. Creation of a collaborative program in DSTO to study the synergic effects of blast and fragmentation on a platform. The majority of improvised explosive device incidents are from near-field detonations involving both blast and fragment effects. Although the physical processes of explosive detonations have been well characterised, the complex interaction of these effects on platforms, particularly in the near field, is difficult to simulate and also difficult to protect against.

As part of the current MPD long range research program investigating underwater explosive effects and associated damage for both submerged and floating naval vessels, there are a number of additional research areas that could be included. These are the study of shock transmission through pipes and the propagation of shock through tanks associated with ships and submarines; compliant coatings, to reduce the shock loading throughout the submarine; and semi-active equipment isolation systems.

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Glossary

Acronyms

2D	Two dimensional
3D	Three dimensional
ADF	Australian Defence Force
AJEM	Advanced Joint Effectiveness Model
ALE	Arbitrary Lagrange Euler
ALON	Aluminium Oxynitride
ARA	Applied Research Associates Inc.
ASAP	US Advanced Survivability Assessment Program
ASLAV	Australian Service Light Armoured Vehicle
CDF	Chief of the Defence Force
CENWO-ED-S	Protective Design Center
CPNI	Centre for the Protection of National Infrastructure
DMTC	Defence Materials Technology Centre
DSTO	Defence Science and Technology Organisation
EFP	Explosively Formed Projectile
ERA	Explosive Reactive Armour
ERC	Explosion Resistant Coating
ERDC-GSL	Engineering Research and Development Centre, Waterways Experiment Station
FATEPEN	Fast Air Target Encounter Penetration
FSP	Fragment Simulating Projectile
FTE	Full Time Equivalent
GFRP	Glass Fibre Reinforced Polymer
GVAM	General Vulnerability Assessment Methodology
HE	High Explosive
HHA	High Hardness Armour
IED	Improvised Explosive Device
JTCG/ME	Joint Technical Coordinating Group for Munitions Effectiveness
LRR	Long Range Research
MPD	Maritime Platforms Division, DSTO
NASA	National Aeronautics & Space Administration (USA)
NATO	North Atlantic Treaty Organisation
NSWC/DD	Naval Surface Warfare Centre, Dahlgren Division
OA	Operating Assignment
R_f	Radius of fireball
RHA	Rolled Homogeneous Armour
RUSI	Royal United Services Institute
SLAMS	Survivability and Lethality Assessment Modelling Software
SLERA	Self Limiting Explosive Reactive Armour
SPH	Smoothed Particle Hydrodynamics
SWET	US Ship Weaponeering and Estimation Tool
TTCP	The Technical Cooperation Program
UNDEX	Underwater Explosion
USARL	United States Army Research Laboratory
US/USA	United States of America
WSD	Weapons System Division, DSTO
XML	eXtensible Markup Language

Terms

Weapons Effects	the effect created by the weapon, e.g. detonation of a 155 mm warhead creates a fragmentation effect and a blast effect.
Terminal Effects	the weapon effect and target interaction.

1. Introduction

As part of the strategic planning process for Maritime Platforms Division's (MPD) long range research program, a series of literature reviews on the current state of various scientific themes were conducted. This particular review focuses on the area of battle damage prediction and collateral damage estimation in the land and maritime domains; or more generally, platform vulnerability and modelling. Protection of the dismounted individual combatant, for example body armour, is not considered.

DSTO has a long history in the study and assessment of the vulnerability of military platforms and the lethality of various munitions. The fundamental principles that form the basis for the study of weapons effects have been captured by B. Walsh [1] in his report 'Vulnerability Assessment Manual of Conventional Weapons'. His report also outlines some of the research that DSTO has been involved with in the terminal effects field prior to 2002.

The current MPD work program includes a range of studies associated with both land and sea platforms. This program includes advice and guidance for operations and the force-in-being; it assesses the technical risk of acquisitions; it supports industry development; and its research, science and technology leveraged through collaboration, positions the ADF to exploit the latest developments and adapt to changes in the conduct of war. Importantly, it also supports the concept development, acquisition and through life support of Defence platforms.

Although a number of countries, particularly the US and UK, have large research organisations working in the fields of protection and weapons effects, access to information on terminal and weapons effects in the open literature is limited. This is due to the security classification of both the protection performance of the various Defence platforms and the actual effectiveness of the weapons against designated targets. From Australia's viewpoint, data exchange within the TTCP community and bilateral arrangements have been invaluable for the transfer of information amongst member countries.

Research in both academia and private enterprise outside the defence community is expanding, particularly in the areas associated with counter terrorism. In the structural engineering field this work has been focussed on building design and protective mechanisms of building structures.

1.1 Current ADF Operations

As at 13 March 2008, Australia was involved in 11 Operations over 8 countries (Figure 1), utilising approximately 4060 people. Of these, the three major operations with respect to personnel numbers and high risk of casualty were:

1. Op Catalyst (Australian Defence Force (ADF) contribution to the rehabilitation and reconstruction of Iraq, 1540 people)
2. Op Slipper (ADF contribution to the international coalition against terrorism in Afghanistan, 1025 people)
3. Op Astute (ADF contribution to assist in the restoration of peace and stability in Timor-Leste, 750 people) [2].

In a speech given by Chief of the Defence Force (CDF), Air Chief Marshall Angus Houston in May 2007 to the Royal United Services Institute (RUSI) conference [3], more than 35,000 ADF personnel have taken part in deployments between 2001 and 2007, peaking in June 2006 when 5,200 people were deployed around the world. The Australian Defence Force, at the time of his speech, had only 51,000 personnel, highlighting this as a significant proportion of the available workforce.

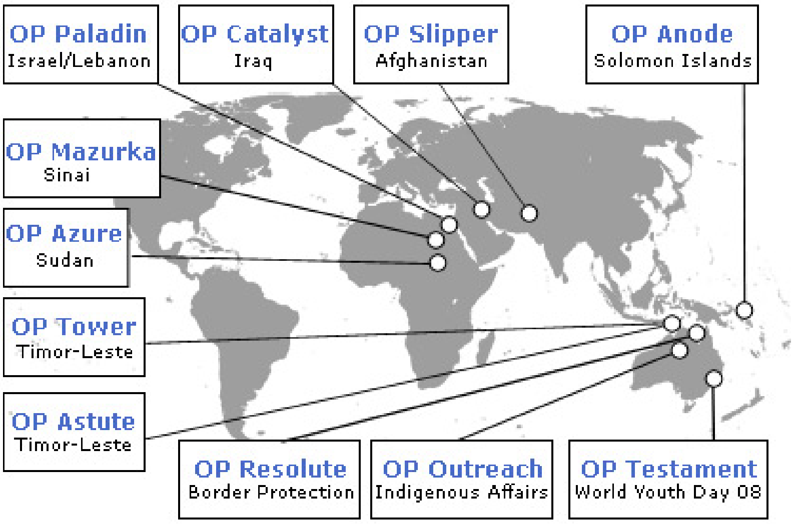

Figure 1: Map of the world showing the location of operations Australian forces are involved in [4]

It was a 'testament to the complexity of our current security environment' [3] that our people were involved in such varied situations, which included border surveillance, fisheries protection and support to United Nations mandated operations.

1.2 The ADF of the Future

In his speech to the RUSI conference, CDF went on to describe the ADF of the future, the shape of the future strategic environment and what we will be called on to do. His vision for the future is one where the ADF is a

> …balanced, networked and deployable force, staffed by dedicated and professional people, that operates within a culture of adaptability and excels at joint and coalition operations…

The force would be supplemented with qualities that include being integrated, survivable, ready and responsive.

While CDF admits that predicting the future is 'tricky business', it is almost certain that 'armed force will remain an important element of international affairs' and that Australia cannot guarantee it will remain free from threats to our national security. Compounding the many threats Australia may face, we also face

> …an environment in which rapid rates of technological change and the altering human organisation of warfare have the capacity to substantially enhance the capabilities of our future adversaries.

With the increasing lethality and precision in certain battlespaces, particularly those with maritime and air force elements, the ADF will seek to 'reduce both the footprint and the vulnerability of deployed forces', while at the same time, they expect to be involved in more operations that are 'low-intensity, particularly stabilisation operations, that require a demonstrably visible presence on the ground' [3].

According to CDF, Defence will need to be able to;

> …defend Australian territory against credible threat without relying on the combat forces of other countries…to provide joint forces to contribute to, or lead, coalition operations in Australia's neighbourhood [and]… further away…we will continue to be called upon to provide regional situational awareness to a global commitment of military force.

In addition to this, Chief of Army's Development Intent [5] states that Army is to be;

> …optimised for close combat in complex, predominantly urbanised terrain, as part of a joint inter-agency task force… all elements of the deployed force are to be provided with protected mobility, firepower, situational awareness and stealth to enable them to perform their missions without undue risk…[and] the Army is to build into its structure a high degree of organisational redundancy and the ability to rotate and replace forces in theatre, hence there should be no 'single-shot' or single-element capabilities in the inventory of land force capabilities.

Finally, CDF recognises that

> Defence may not always be the lead agency for dealing with security challenges, and we need to be prepared for, and highly capable at, working with other government departments.

1.2.1 DSTO's role in Supporting the ADF of the Future

Many of the factors mentioned by CDF, including the complex nature of the conflict environment, mean that Defence must be predictive and reactive in nature, always trying to position our forces in the best possible position to defeat the enemy. DSTO has a crucial role in this, in ensuring that the tools and resources provided to the ADF will enable our forces to perform their role to their most capable.

Some of the National Security research occurring to date within DSTO is linked with the Attorney General's Department and the Department of Foreign Affairs and Trade. With the existing leverage through TTCP and bilateral agreements and the standing up of the new Defence Materials Technology Centre, these types of linkages are further strengthened between DSTO, our allies, universities and industry—vital to better positioning the ADF for the future, in the event that Defence is not the lead agency for dealing with security challenges.

The highly specialised nature of the work to support the ADF of the future means that regardless of whether or not the work is being conducted elsewhere, DSTO must know how and why such things behave as they do or were developed in a particular way, to ensure the Commonwealth is an informed buyer. A simple example of this is the application of inappropriate ballistic test standards in armour procurement specifications. The specification and application of requirements to specific military needs for the protection of platforms from specific threat sets requires a specific skill set which is contained within the Defence community. The use of civilian standards or specifications that are inappropriate for the acquisition can result in lengthy procurement problems or serious consequences on the battlefield [6]. DSTO's involvement in the development of these specifications maximises the chances that innovative or appropriate solutions are applied and reduces the technical risk associated with future acquisition projects.

1.2.2 Multilateral Agreements

Late in 2007, the formation of a new Defence Materials Technology Centre (DMTC) was announced, which partners DSTO with universities and industry to research various materials relevant to Defence applications. Through the DMTC, a number of developmental armour material related topics will be investigated, such as:

- High strength steels for Defence Applications
- Multi-functional composite materials
- Evolution of steel based vehicle systems and armour protection
- Comparative evaluation of hybrid metallic, ceramic, composite and titanium materials for vehicles

Work within the DMTC commenced mid 2008, with funding for the next 7 years provided under the Defence Future Capability Technology Centre. It is expected that results from topics such as the comparative evaluation of materials for vehicles will directly impact armour acquisition programs in the future, including LAND400—the replacement of Army's armoured vehicle fleet.

In addition to this centre, DSTO also receives significant information on vulnerability reduction methods, including armour technology, through both multilateral (TTCP) and bilateral arrangements.

2. Vulnerability vs. Lethality

Before discussing the various aspects of vulnerability assessments or weapons effects, it is necessary to define some commonly used terms, in particular, the inter-relationship between the terms “vulnerability” and “lethality”. Essentially, a vulnerability assessment is a measure of the effectiveness of an item, such as a vehicle, ship or human, to resist weapons effects. Lethality is a study of the ability of the weapon (projectile, fragmentation, blast, shock) to defeat the target. Both terms reflect the interaction between the weapon and the target, but from a different perspective [1].

A vulnerability assessment requires characterisation of the weapon effects (shock, blast, fragments and penetrators); a description of the target’s physical attributes (e.g. a 3D model of a ship or perhaps just a simplified box) and an examination of the interaction of the weapon and target to determine the consequences for a target’s capabilities (terminal effects). Vulnerability assessments of platforms can be used for a variety of purposes including, assessing the benefit of various design solutions, measuring the effectiveness of vulnerability reduction solutions and also to provide input into warfighting scenario simulations.

Within Maritime Platforms Division, research is concentrated on reducing the vulnerability of a platform from various threats, rather than optimising the lethality of weapons. As such, much of this report is focussed on vulnerability reduction methods rather than lethality. However a number of tools used in the prediction of weapons effects can have application to vulnerability analysis, as will be seen in the following sections.

This paper provides a background section to the science behind terminal effects and some relevant weapon effects; this is followed by discussion on the physical protection of assets against these threats through the use of armour systems, to give the reader an appreciation for the materials that are used.

The heavy emphasis on modelling and simulation to solve problems within the battlefield context is obvious. The destructive nature of the many tests combined with the high cost of both the platforms and weapons involved, makes it nearly impossible to conduct full scale one to one tests of new equipment. If tests are conducted, they are ‘one off’ tests at best and therefore provide limited data for the analyst to validate their models. Further data is gained from the battlefield space itself, however again although realistic, such data is difficult to quantify for validation purposes. I.e. the amount of explosive and stand-off distance may never be known.

The complexity of being able to realistically simulate and model the interaction between the detonating weapon and the platform systems is further complicated due to the high strain rate regime and multi-phase loading conditions within which the damage is occurring.

3. Ballistic, Fragmentation and Explosive Damage

In order to assess the vulnerability of a platform, it is important to first have an understanding of the nature of the threat. Terminal effects research can be broadly split into two sections; in-air explosions focussing on blast and fragmentation and underwater explosions (UNDEX) focussing on shock and bubble physics; and their effects on the platform. There are similarities, but there are also some very different effects, both of which are detailed in the following section.

3.1 Fragmentation and Ballistic Damage

Ballistic and fragmentation damage both involve the impact of a target by a penetrating object, however the damage mechanisms are very different. Ballistic damage is generally caused by the impact of a target by a projectile fired from a firearm. The projectile shape is designed to be aerodynamic and is optimised for penetration. A hard surface such as high hardness armour steel will often provide good protection against ballistic threats.

Fragmentation damage is caused by the impact of a fragment propelled by a fragmenting warhead or an improvised explosive device (IED), for example. Fragments can be irregular in shape and size and will often impact the target with a blunt or jagged surface. In this case, a more ductile armour material can often be more effective than hardened steel.

3.1.1 Ballistic and Fragmentation Damage Prediction

Experimental testing is the most common method for ballistic and fragmentation damage prediction as it is generally more time effective than analytical and numerical methods, and can usually be conducted at a reasonable cost for coupons. The experimental testing of fragment damage can be conducted either as a full scale test with a fragmenting munition, or simulated in the laboratory using fragment simulating projectiles (FSPs). For the design and assessment of new materials and structures it is important to understand how they respond to projectile and fragmentation attack.

Analytical codes are available to predict ballistic penetration and fragmentation effects; these are discussed in a later section. Numerical modelling is also gaining popularity in ballistic damage prediction as codes and computers become more advanced.

3.2 Air Blast Explosive Damage

When explosives detonate in air, gaseous detonation products expand rapidly resulting in damaging effects, Figure 2. Depending on the distance from such devices, the damage mechanisms resulting from their detonation vary greatly. These blast damage regimes can be separated into the following categories as supplied by Ritzel [7] at a short course on Blast Physics, Damage and Injury:

Figure 2: Air blast experimental test. This image was taken during a field trial for CTD-14: Demountable Strongpoints [8]

Detonics Regime: The target is in direct or near contact with the explosive, typically less than $0.5R_f$ (where R_f is the radius of the fireball). The interaction with the target inside the fireball is dominated by the physical flow of detonation products. Most damage is inflicted by the expansion and kinetic energy of the detonation products. The pressure in this zone is ~1,000 to 100,000 atm (normal atmospheric air pressure can be assumed to be 1 atm).

Near-field Regime: The target is just beyond the fireball, typically less than $2R_f$. There is a complex shock structure with no negative shock phase, multiple components (fireball and air-shock considerations) and strong after-burn effects. Models must account for impingement of the fireball and detonation products in addition to the air-shock phenomena. The pressure in this zone is approximately 10–1,000 atm.

Mid-field Regime: $2R_f$ to $10R_f$. The target encounters a non-uniform shock structure, single phase (pure) air-shock (no fireball or detonation products) and non-scalable after-burn effects—afterburning changes with charge size. The pressure in this zone is approximately 0.1–10 atm.

Far-field Regime: The target is at some distance from the initiation point greater than $10R_f$. In this region the blast profile is similar to the idealised or "typical" profile, with a significant negative phase and only air-shock to consider. There are non-scalable after-burn effects. The pressure in this zone is less than approximately 0.1 atm.

3.2.1 Air Blast Damage Prediction

In the current ADF operations of concern, most weapon / target interactions will be located in the detonics, near-field or mid-field regime. The far field regime is most relevant for nuclear blasts, where the blast wave maintains significant destructive energy to large distances from the point of detonation.

Because of the complexity of the detonics, near-field and mid-field regimes, damage prediction in these regions is more complex than in the far-field regime. In addition to this, the actual loading on the target can be complicated by the interaction of the target response and the blast loading condition. For this reason full scale experimental testing is by far the most accurate method for analysing blast damage effects. However, full scale experimental trials are costly, so numerical modelling and simulation is still required. Numerical modelling and simulation of air blast events is discussed in a later section.

3.3 Synergistic Effects of Blast and Fragmentation

An area that requires immediate attention is the synergistic effects of blast and fragmentation effects on a target. In developing numerical methods to handle the physical phenomena of blast and penetration, researchers have treated the two effects independently. For far-field effects this is usually justified as the fragments have separated from the blast wave. In the near field it has been shown that the loading and failure mechanisms occurring require that the combined effects are understood.

It has long been seen that weakening of a structure due to the fragment damage will cause the failure criteria of the structure to alter. For example, a bare charge in a box will cause a completely different failure mechanism to the same size charge containing a number of fragments.

Traditionally this problem has been solved by using semi-empirical equations based on critical damage radii for the near-field effects and more detailed algorithms once the effects of the blast and fragment penetration can be resolved.

Currently, research is being conducted through TTCP looking at the blast / fragment problem from both the weapon design and also the synergistic effects of the combined loading on the target. The design of protective mechanisms will require more detailed numerical formulations of this problem. Testing of armour for near-field events needs to be with realistic weapons.

The other driving force in understanding the combined effects is the development of new directed fragment weapon designs, which will also require simulation to assess the effectiveness of different designs.

3.4 Underwater Explosive Damage

Maritime weapons such as light and heavyweight torpedoes [9], ground, moored and buoyant mines [10] and underwater improvised explosive devices [11, 12] cause damage through explosively driven fluid effects. An understanding of these processes allows for the design of structures that are optimised to resist underwater explosive effects, and conversely, design weapons of greater lethality. Such expertise also provides tactical guidance for maritime operations.

An underwater explosion (UNDEX) emits a high pressure shockwave and its gaseous reaction products create an underwater pulsating bubble [13-15], both of which can cause damage to proximate structures (Figure 3).

Figure 3: UNDEX Shock test of HMAS Hawkesbury, 1999 [16]

An underwater explosive shockwave impinging on a structure effects damage by a high pressure transient load, which may additionally be followed by a shock-induced cavitation reloading.

An UNDEX bubble, Figure 4, can cause damage through the effects of bubble collapse & jetting, bubble pulse, and whipping (a violent whole body longitudinal flexing of the vessel).

Bubble damage is a short range effect and is therefore always in addition to UNDEX shock damage, however it can be a significant addition [17]. There are engineering methods available to reduce the effect of UNDEX shock, but presently there are no mitigating technologies to reduce bubble effects.

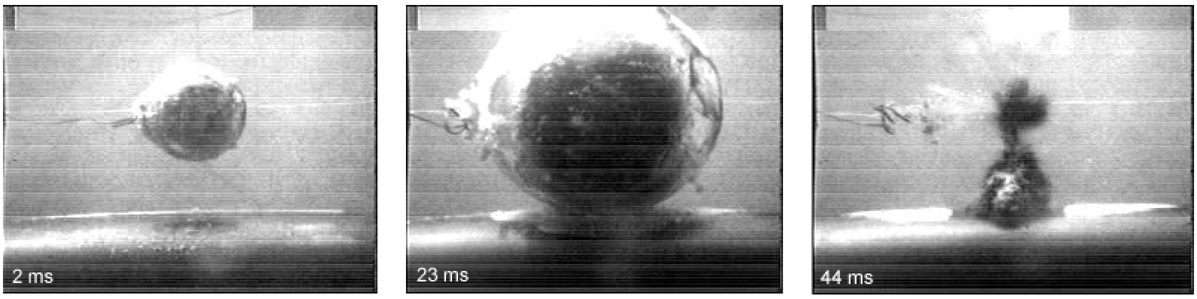

Figure 4: A series of high speed camera images tracking the formation and collapse of an explosive bubble on to a steel cylinder [18]

3.4.1 UNDEX Damage Prediction

The three common methods used to assess UNDEX shock effects on structures are the shock factor methodology, shock response spectra and finite element analysis methods.

3.4.1.1 Shock Factor

Shock factor is a method used to estimate structural deformation based on scaling laws. These laws have been known since at least the early to mid 20th century [19-22].

In principle, an experiment is used to determine the deformation of a structure for a particular explosive charge mass and range (distance of structure from the charge), after which scaling laws can be used to infer damage for other combinations of charge mass and range.

In its simplest form it is known as the Hull Shock Factor, and is used to assess the severity of the shock at particular locations on a structure. In a modified form it is the Keel Shock Factor, an assessment of the severity of the shock for ship hulls, and similarly, as the Item Shock Factor for equipment.

Shock Factor is an approximate measure of the severity of the shock and is more suited to gross structural deformations such as fracture, tearing, deformation, hull plate dishing, hull rupture, pipe rupture and breaking of the keel [23].

The presence of the sea surface, seabed and the type of explosive used require further corrections to the shock factor damage assessment formulae.

3.4.1.2 Shock Response Spectra

Biot developed the method of shock response spectra to calculate maximum stresses in buildings subject to earthquake induced loads [24]. This method was later adapted to assess shock loads on platforms, equipment and equipment mounting systems.

A shock response spectrum measures the response of a single degree of freedom simple harmonic oscillator to a load function. It calculates the maximum acceleration, pseudo-velocity and displacement for a simple harmonic oscillator both during the applied load and following its cessation.

It is a method best suited to operation and safety assessments of elastic, lightly damped systems of items of equipment and their mountings. A test or standard stated in terms of a shock response spectrum allows flexibility in how the test load is created, be it drop table, floating platform or in-service explosive shock testing.

3.4.2 Application of shock analysis

Two fields of study have been identified, in which the application of shock analysis could be applied in the future:

1. Underwater explosive shock can be transmitted into the interior of a submarine by seawater piping. Submarine systems that are reliant on a seawater source, directly or indirectly, are the auxiliary seawater and freshwater cooling systems; ballast and trim systems; potable, chilled and demineralised water systems; battery cooling system; diesel engine seawater cooling system and weapon discharge systems. Each system is potentially at risk of shock damage. A shock propagating through a fluid filled pipe will suffer attenuation, dispersion and multiple reflections and interact with valves, penetrators, constrictions and pipe bends. A study of shock in pipes will allow transmitted shock loads to be determined and methods of shock reduction to be explored.
2. A submarine has tanks for the ballast, trim, fuel, weight compensation and weapons discharge systems, each of which will influence the shock load on the submarine's structure. The shock response is governed by how full the tank is and what fluid it is filled with. Assessment of the effects of shock in tanks can also be applied to understanding shock effects on double hulled submarines.

4. Vulnerability Reduction Measures

The challenge for the platform designer is to be able to provide a realistic level of protection to the platform and its occupants but maintain a level of war fighting capability that the defence force requires. In providing realistic levels of protection it is imperative for DSTO to inform Defence of the ability of the various designs to meet these requirements, but to ensure the requirements themselves keep abreast of innovative solutions.

The protection of the platform should be matched with the threats that the platform is expected to encounter; however one difficulty is that weapons and threats change over time. For example, more than 90 different ways of initiating an IED have been encountered, which presents a significant difficulty to develop jamming countermeasures [25]. Some of these initiators have no premature-initiation countermeasure. The final line of defence against such threats is to mitigate the overall damage to the platform by a protective system such as armour.

It is important to understand that the survivability of a platform, and hence reduced vulnerability, depends not only on the protection that its armour provides, but its mobility and capability to return fire. Hence there will always be a trade-off between the protection levels provided and other competing requirements for the available weight, cost and space.

Vulnerability reduction measures include armour to prevent the penetration or transfer of the weapons effects, the design and layout of systems to minimise the effects of a weapon (e.g. shock isolation) and also the protection of vital components within the platform.

This chapter provides an outline of some of these vulnerability reduction measures as well as future concepts in both metallic and non-metallic materials for land and maritime platforms.

Underwater platforms are not typically concerned about ballistic and fragmentation protection, but they do incorporate shock protection measures.

4.1 Armour Solutions

A range of armour and protective solutions have been developed, or are being developed to suit both the threat and environmental requirements they are exposed to.

4.1.1 Metallic Armour

Metals have been used as armour for hundreds of years, from chain mail to battle tanks, and they still remain the primary material for many armour systems. They can perform as a structural component at the same time as providing protection from various threats, including blast and projectiles. The main metallic armours are steel, titanium, aluminium and magnesium. The baseline metal for combat vehicle applications is rolled homogeneous armour (RHA) steel [26]. When considering other armours they are usually compared to an equivalent weight of RHA. High hardness armour (HHA) steel has superior ballistic performance compared to RHA. However RHA provides better fragmentation protection and has better weldability.

An example of metallic armour used as an appliqué is shown in Figure 5. The figure depicts the steel hulled Australian Service Light Armoured Vehicle (ASLAV) fitted with bar armour. Bar armour is used to defeat rocket propelled grenades and the spacing of the armour from the hull of the vehicle is precisely designed against this threat.

Figure 5: Australian Service Light Armoured Vehicle (ASLAV), showing examples of metallic (vehicle hull) and spaced (bar) armour [27].

4.1.2 Transparent Armour

Traditionally, transparent armour consists of layered glass and/or plastic separated by polymeric interlayers. Polycarbonate is the most common plastic used for transparent armour as it is relatively cheap, provides good ballistic protection, and is easily formed or moulded. The first layer of transparent armour is usually a hard brittle material, often glass, designed to break up, deform and erode the incoming projectile and absorb some of its kinetic energy, spreading the kinetic energy over a wider area. Subsequent layers provide additional resistance, and the rear-most layer is a non-spalling plastic layer such as polycarbonate, to stop the projectile without allowing glass, plastic or projectile fragments to penetrate.

Currently, transparent armour must be very thick to be effective and hence adds significant weight. It may also produce optical distortion. Furthermore, only certain types are suitable for use with night vision goggles. New materials to provide better protection, improved optical properties and reduced weight are being explored. For instance, transparent crystalline ceramics are being considered as a replacement for the first impact layer, as they are stronger and lighter than conventional glass / plastic systems. The U.S. Army Research Laboratory (USARL) has identified three major candidate ceramic materials for use as the strike face of a transparent armour system. Each has its own advantages and disadvantages. The candidates are aluminium oxynitride (AlON), magnesium aluminium spinel (spinel), and single crystal aluminium oxide (sapphire) [28]. Current limitations of such materials are their high cost and sizes that are available; however several programs are being conducted at the USARL investigating the cost reduction and scale up of these materials.

Figure 6 shows transparent armour installed on the windscreen and side windows of an Australian Bushmaster vehicle. Transparent armour requirements have also been identified for other land and sea platforms, and an extra requirement for minimal optical distortion of thick transparent armour has also been identified.

A number of premature failures of glass systems are being found in theatre, where it is exposed to extreme temperature variations. These non-ballistic failures include delamination, moisture ingress, coating debonding and surface scratching of inner and outer ply materials. Investigations are underway through TTCP to improve the durability of the procured product.

Figure 6: Australian Bushmaster infantry mobility vehicle with transparent armour windscreen and side windows [29]

4.1.3 Ceramic Armour

Ceramics are used effectively as armour due to their high compressive strength and hardness. They are lighter than traditional metallic armours but still provide very good ballistic protection. Due to the very low strength of ceramics in tension, they are usually used as an initial strike face attached to a more ductile backing plate such as a metal or fibre composite. The ceramic helps break up projectiles and dissipate kinetic energy, and the backing plate provides structural integrity, increases overall system stiffness and captures ceramic and projectile fragments.

Due to the brittleness of ceramics, small tiles or ceramic beads are often used to increase the multi-hit capacity of the armour. This means that usually only the tile or bead that is impacted by a projectile is destroyed, but the surrounding tiles may maintain their integrity. Damage to adjacent tiles is further minimised by ensuring proper adhesion of the ceramic to the backing and cover, preventing lateral displacement of the material during penetration. Unfortunately, smaller tiles mean more tile edges, which offer minimal resistance to penetration. Cracking can also be considered similar to tile edges, in that it creates a locally weak or inhomogeneous area. So, unlike metallic armour, trade-offs must be made between the ability to withstand multiple closely spaced hits, and the overall ballistic protection level achieved.

The ceramics commonly used in armour applications are boron carbide, silicon carbide and alumina. Boron carbide is the lightest of the three and is used for helicopters and certain body armour plates, but it is very expensive. Alumina, whilst cheap, is quite heavy. Silicon carbide is currently the material of choice as it provides a trade-off between the two extremes and favourable performance against specific threats. There are various methods used to produce silicon carbide, but many do not lead to favourable ballistic properties.

Unfortunately, to date there is no one mechanical or material property to rank ceramics based on their likely ballistic performance, it can only be determined by costly ballistic testing. Current research in the ceramics community aims to develop a low cost ballistic test protocol to test candidate ceramics and ultimately rank them against certain criteria, but this will still require ballistic testing.

4.1.4 Reactive Armour

The most common type of reactive armour is explosive reactive armour (ERA)—add-on armour that consists of an explosive sheath sandwiched between thin metal plates. The armour explodes when it is impacted by an explosive charge, disrupting the incoming charge or plasma jet so that it can be stopped by the backing armour. It is particularly effective against shaped charges and long rod penetrators, depending on how it is designed. It usually consists of tiled elements, Figure 7, so that only the element that is impacted is destroyed, allowing for a better multi-hit capability in a broad sense. Hazell [30] provides a good review of the current main development trends in ERA. Advances such as the use of multiple plates, alternative materials and improved explosive compositions are discussed.

Figure 7: Example of explosive reactive armour as applied to a tank [31]

4.1.5 Liquid Armour

Shear thickening fluids are liquids that behave like solids when a shear stress or force is applied. They are being considered for use in armour because this property allows them to move freely until impacted by a high velocity projectile, which will cause them to harden and absorb the projectile's energy. They would be used in conjunction with existing flexible armour such as Kevlar, but would decrease the amount of Kevlar required, hence improving flexibility. They are currently being considered primarily for body armour, but may have application in other areas.

4.1.6 Explosion Resistant Polymer Coatings

A number of new materials that can reduce the severity of the structural damage due to blast effects are becoming available. Various government and commercial organisations around the world have begun conducting research into these explosion resistant polymer coatings. The mechanisms by which these coatings enhance blast protection, as well as the optimum material properties required to provide maximum performance are not yet fully understood [32].

To date, the focus has been on using existing materials in new applications. For example, polymer coatings previously developed by the Line-X company for sound damping in the transport industry are now used for blast mitigation on the Pentagon [33]. Understanding how these materials mitigate blast is a key factor in developing and optimising their use and performance. Predicting the performance of these materials has been limited due to the complicated failure and deformation mechanics involved under blast conditions.

The use of these coatings for military and civilian applications is promising and they have already been shown to enhance vehicle blast protection [34]. DSTO has begun exploring the modelling and experimental verification of these materials and once accurate models have been developed to predict the performance of existing materials then a numerical search may begin to explore which material properties are most influential. This research program will also count towards a Doctor of Philosophy degree [35].

4.1.7 Composite Armour

Composite armour is a broad term for armour that combines different materials such as ceramics, metals, plastic, honeycomb, fabrics or air. These are often layered in a sandwich type structure. Composite armour provides great scope for many new armour solutions including aircraft armour, spall liners and light weight armours. Composite armour is used primarily in the lightest weight applications and commonly incorporates Aramid or Ultra High Molecular Weight Polyethylene. Occasionally fibre reinforced composites such as glass fibre reinforced polymer (GFRP), S2 or E glass are also used. Lightweight composites such as these can defeat ball round threats when laminated as a stand-alone system, but to defeat larger calibres and armour piercing ammunition they must be used in conjunction with a hard material such as a ceramic. Some problems also exist with deformation of the back face of many composite armours. The back-face deformation can not only cause significant blunt force trauma to a body in contact with it, it can also cause the adhesive bond between the armour and the vehicle hull to weaken and the panel to potentially detach.

4.1.8 Complex and Special Armour Systems

Complex and special armour systems are very heavy and are usually applied to main battle tanks, as they are designed to mitigate highly energetic threats of current significance. They are also gaining interest for lighter vehicles, so there is a strong driver for innovative solutions.

The explosively formed projectile (EFP) is a difficult weapon to protect against since it is designed to penetrate very thick armour. An explosively formed projectile is similar in design to a shaped charge or rocket propelled grenade, that is, it consists of a slightly rounded copper disk, encased in explosive. When detonated, the explosive forms the copper into a very high kinetic energy plug that has extremely good penetration characteristics. Developing light weight solutions to defeat such threats would not be a simple task.

4.1.9 Cellular Materials

Cellular materials have been shown to provide increased blast protection properties compared to monolithic plates of equal mass. Xue and Hutchinson [36] used finite element simulations to compare three different core topologies under impulsive loading with a solid plate of equal mass. They found all three sandwich plates were capable of sustaining larger blasts than the solid plates. They also recognised that there is considerably more advantage for the use of cellular structures in water blasts due to the fluid structure interaction. Fleck and Deshpande [37] confirmed this in a parallel study in which they developed a design procedure for analysing the blast resistance of clamped sandwich beams with cellular cores. They found that an order of magnitude improvement was achieved for water blast whereas only a moderate gain was found for air blast compared to monolithic constructions. Bahei-El-Din and Dvorak [38] showed that the use of a polyurethane or polyurea interlayer used in a sandwich plate in conjunction with a metallic foam core lead to improved blast resistance compared with the foam core alone.

To successfully implement these materials into blast protection designs, the failure mechanisms, effects of fatigue and corrosion, environmental durability and the optimum topologies to resist blast must be better understood. The manufacturing methods may also need to be refined to reduce the cost of production in some cases. A four nation TTCP operating assignment is in the proposal stage to further look into cellular materials for blast/ballistic mitigation and force protection.

Metallic sandwich structures with cellular cores have shown potential for use as lightweight blast mitigating armour material. Figure 8 shows some of the core topologies that are available [37].

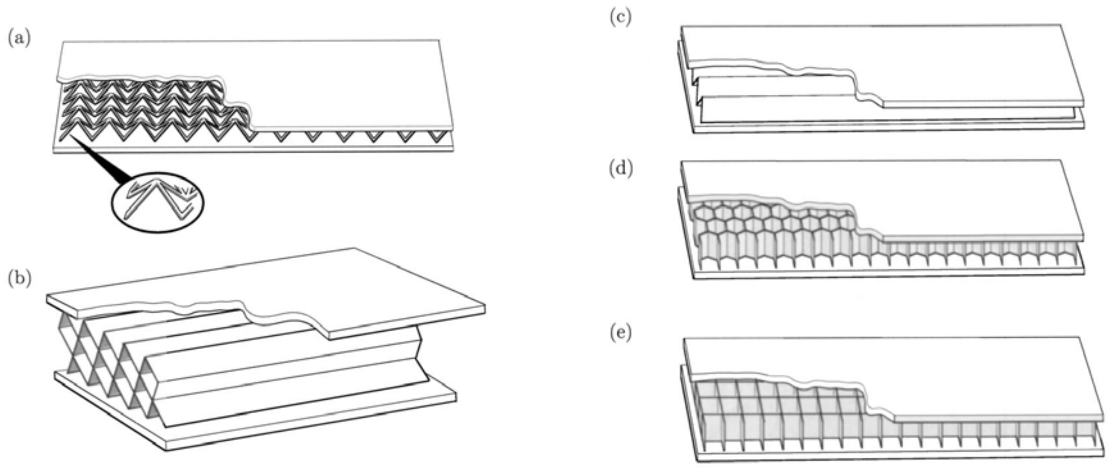

Figure 8: Examples of cellular core topologies; (a) pyramidal core, (b) diamond-celled core, (c) corrugated core, (d) hexagonal-honeycomb core, (e) square honeycomb core [37]

These materials have been shown to provide increased blast protection properties compared to monolithic plates of equal mass. They are recognised as being considerably more beneficial in water blasts compared to air blasts due to the fluid-structure interaction.

4.1.10 Compliant Coatings

It has been observed [38] that a closed cell compliant neoprene layer bonded to a steel plate reduced the underwater shock load on the plate and repelled the underwater explosive bubble. Without the coating not only was the load higher, but also the bubble was attracted to and collapsed onto the plate. Understanding the mechanism behind this protective effect and how it scales with explosive charge size will determine whether it can be exploited for in-service UNDEX protection.

4.2 Structure Protection

While the focus to date has been towards vehicles, it is possible to directly transfer some of the technology over to infrastructure protection. The technology gap created is in regard to building materials such as concrete and timber that are not used in vehicle design. These materials have been under investigation for many years in the open literature and have reached maturity for common products such as reinforced concrete. Some of the newer reinforced concretes such as the steel or glass fibre concretes are less mature, but their blast resistance is being proven experimentally [39]. Research in this area, for example, and transition of lessons learnt in the vehicle protection arena to structures, could provide a valuable boost to DSTO's National Security initiative.

4.3 Component Protection

Mitigation of the effects from weapons, especially in the UNDEX environment can be accomplished by clever layout and attachment of vital pieces of equipment to appropriate well protected areas of the platform.

4.3.1 Equipment Shock Isolation

Equipment shock and blast loads can be reduced by installing shock mounts between items of equipment and any bulkhead, deck or hull mounting points. Depending on the application, a mount may use wire, an elastomer, spring or deformable metals, but they are all passive devices. Active or semi-active suspension systems will out-perform passive systems and may be appropriate for high value, critical items. It is also noted that mounts designed to reduce the transmission of machinery noise and vibration to the hull can exacerbate shock damage [40], therefore shock protection systems and vibration isolation systems should be carefully designed not to interfere with the function of the other.

5. Modelling and Simulation Tools

The development of modelling and simulation tools for the prediction of conventional high explosive (HE) weapons damage to armoured systems has historically been the domain of the armed forces of various countries.

To be able to realistically model a weapon/target interaction, the driving force within the defence environment is twofold: the cost of hardware and war fighting operational reasons.

The first driving force, the cost of both weapons and military hardware, makes it imperative that the warheads are designed to be effective against their intended targets. The cost of an anti-ship missile will be in the million dollar range and few defence forces can practice with these weapons to validate their effectiveness. Conversely, military hardware needs to be survivable within its likely threat environment—a multi-million dollar warship could in theory become disabled by a small cheap high explosive (HE) round or fragment that penetrates into the operations room if the ship is poorly designed.

A major limitation in developing realistic simulation tools and models is the availability of validated data. Due to the destructive nature of the testing only limited tests can be generated for known scenarios and the cost of full scale tests is either prohibitive or not practical. Data sets originating from real battlefield scenarios are invaluable to provide information on damage mechanisms, but can be of limited value in defining the models as the initiating conditions are rarely known. A problem arises in the need to extrapolate the results from these tests to other scenarios.

The validation of data requires that the characteristics of the entire measurement chain (instrumentation) be known [41, 42]. These characteristics are part of a data's provenance and allow for the data to be used, reused and shared, perhaps in ways unforeseen. It ensures that the greatest use is made of limited data.

The other driving force for simulation and modelling is the war fighting operational requirement. Simulation tools are required to provide accurate information to allow the planning of the battle space. These models are used for a number of purposes including calculating safety templates for various weapons, planning encampment layouts and providing number and distribution of weapons required to achieve a target kill.

There is continual competition from structural engineers in developing mechanisms to protect against the effects of a detonating warhead and the weapon designers in the development of warheads to defeat these protective mechanisms. This has resulted in the development of an extensive array of algorithms and simulation tools to simulate these interactions. A selection of the most common simulation tools and models are summarised within Appendix A of this paper.

A wide variety of simulation tools are used to conduct specific analyses of platform vulnerability to blast, fragment penetration and shock. Previously, a somewhat natural separation of domains existed for these simulation tools, based on the target definition e.g. naval, air, ground and personnel. However, it is evident that some of the methods implemented as part of their respective simulations have applicability across domains.

5.1 Model Selection

The basic criteria used in classifying tools are based on the fidelity of the solution and therefore the amount of detail available on the weapon and the target needed to derive the solution. Remennikov [43] and other reviewers of this area have used the following criteria for assigning tools for blast effects. It is generally a good starting point for classifying most weapon effects simulation tools.

The following methods are available for prediction of weapon effects on structures:

- Empirical methods
- Semi-empirical methods
- Numerical (or first-principle) methods

Empirical methods are essentially correlations with experimental data. Most of these approaches are limited by the extent of the underlying experimental database. The accuracy of all empirical equations diminishes as the explosive event becomes increasingly near field (closer to the detonation point).

Semi-empirical methods are based on simplified models of physical phenomena. They attempt to model the underlying important physical processes in a simplified way. These methods rely on extensive data and case studies. Their predictive accuracy is generally better than that provided by the empirical methods.

Numerical (or first-principle) methods are generally based on mathematical equations that describe the basic laws of physics governing a problem. These principles include conservation of mass, momentum, and energy. In addition, the physical behaviour of materials is described by constitutive relationships.

Both empirical and semi-empirical equations are used extensively in vulnerability studies and for war-fighting operational studies. The underlying assumptions and validity to the actual scenario being modelled must be understood, otherwise large errors will occur or a large investment will be made in developing overly detailed models, which will not provide more accuracy to the result.

Most vulnerability codes currently require the failure criteria of both structural elements and components to be input as data. These input criteria are measured from experimental data or numerical methods.

5.1.1 Blast and Penetration Methods.

The basic physical principles of blast and penetration are well defined, at least in the far field for the former. For blast, the principles and code developments have been based on free field explosive measurements, particularly from nuclear blast tests. As mentioned in Section 3.2, the difficulty for the application of blast effects on structures is that to model the actual loading on the target can be complicated by the interaction of the target response and the blast loading response, as well as ground interactions. For near-field events this usually results in the analyst making assumptions based on far-field events to make the loading pattern easier to understand. However for the design and modification of protective devices, detailed numerical analysis is required and the two effects cannot be handled separately.

A number of codes that can be used to predict the effects of blast and penetration are detailed in Appendix A. Many of these are distributed by the US army corps of engineers [44] to US government agencies and their contractors. The main codes include CONWEP, BLASTX, BEEM, and SHOCK.

Specific algorithms have been generated to predict warhead fragmentation. The three codes used historically for this have been based on algorithms within CONWEP [45], FATEPEN [46] and THOR [47].

5.1.2 General Vulnerability / Lethality Assessment Methods

The current development of vulnerability assessment simulation tools tends to be the amalgamation of many smaller tools into one major simulation tool-kit. The development of computer memory and power has meant that more detailed models can be used within this framework. It should be stressed that the detailed models have allowed for more realistic scenarios to be evaluated, but the underlying semi-empirical equations have not always kept up with these developments.

Many countries have developed an in-house assessment methodology to model the vulnerability of their specific assets. These include:

- Australian CVAM / XVAM [48], for ship, air and land vehicle vulnerability;
- UK SURVIVE [49] and MAVKILL, ship and submarine vulnerability and land vehicle armour optimisation tools;
- Canadian GVAM, SLAMS [50], ship vulnerability and land vehicles;
- US ASAP [51] and SWET, survivability assessment and ship weaponeering tools.

The US Advanced Joint Effectiveness Model (AJEM) is a Department of Defense standard computer simulation for evaluating the lethality and terminal effectiveness of munitions and the vulnerability of aircraft, missiles and ground-mobile systems to weapons effects.

Due to the complex nature of the weapon / target interactions and physical phenomena being analysed, it is extremely important for the user of these codes to have a good understanding of the underlying assumptions and limitations of the models. A significant limitation for all of the vulnerability codes is in defining realistic failure criteria for both the structural elements and the system components which reflect the scenario being evaluated. E.g. depending on the scenario, the failure criteria for a human may be set as the blast to cause a burst ear drum, for another scenario it may be set to a higher blast level to cause significant injury.

One area that has major limitations is the failure of components from combined blast and fragment damage. This is an emerging area of research interest.

5.1.3 Numerical Simulation

The ability to design new warheads or develop new protective mechanisms requires detailed knowledge of the physical phenomena involved in the warhead / target interaction. The environment consists of high dynamic forces and large plastic deformations. The high strain rate regime is generally unique to military applications, making the adoption of commercial software and techniques difficult.

5.1.3.1 Finite Element Analysis

Broadly, a finite element analysis of a structure requires a numerical model incorporating geometry, mesh, materials, loads and boundary conditions from which its dynamic behaviour can be solved [52]. Post-processing of the results is used to present the pertinent features of the solution set.

In the UNDEX environment, this method requires far more detail than either the shock factor or shock response methods, although ever increasing computing performance and standardised protocols are resulting in larger and more detailed models.

To ensure that the results of a simulation do not display mere verisimilitude, the use of a code should be conducted in accord with, for example, the guidelines of the National Agency for Finite Element Methods and Standards [53].

5.1.3.2 Smoothed Particle Hydrodynamics

Smoothed particle hydrodynamics (SPH) is being increasingly used to model fracture and fragmentation of brittle materials, as well as fluid motion [54]. With this method, material regions are modelled by densely packed particles. SPH has several benefits over traditional grid-based techniques. Firstly, SPH guarantees conservation of mass without extra computation since the particles themselves represent mass. Secondly, SPH computes pressure from neighbouring particles rather than by solving linear systems of equations. Finally, unlike grid-based techniques which must track fluid boundaries, SPH creates a free surface for two phase-interacting fluids directly since the particles represent the denser material (e.g. water) and empty space represents the lighter material (e.g. air). For these reasons it is possible to simulate fluid motion using SPH in real time.

One drawback over grid-based techniques is the need for large numbers of particles to produce simulations of equivalent resolution. Most particles in an UNDEX simulation will be used to fill water volumes which are never rendered. Accuracy can also be significantly higher with sophisticated grid-based techniques (such as particle level sets) [55].

Several research groups within MPD are currently using, or planning to use the SPH technique for the simulation of a number of different problems. These include the relative motion of a landing craft and the mother ship in a well dock scenario, sloshing within hulls, underwater explosion events, the deployment and retrieval of autonomous vehicles and ballistic impact on ceramic targets.

DSTO, in collaboration with the Australian Maritime College [56, 57], have applied a smoothed particle hydrodynamics code to model UNDEX bubbles. With success in modelling the simpler 2D, 3D and 3D interacting bubbles, the program continues to investigate the application of the SPH method to increasingly more detailed models.

6. Summary and Recommendations

Maritime Platforms Division (MPD) has a long and well established expertise in the areas of explosive blast and ballistics effects on Australian Defence Force (ADF) platforms. This expertise allows DSTO to provide advice and guidance for operations and the force-in-being; provide science and technology support to acquisitions; support Defence industry development and position the Australian Defence Force to exploit the latest developments and adapt to changes in the conduct of war.

The complex nature of the conflict environment means that Defence must be predictive and reactive in nature, always trying to position our forces in the best possible way to defeat the opposition. This report highlights current ADF operations, and provides the context in which research in platform vulnerability and battle damage prediction is essential to maintain ADF's war fighting capability.

This report provides a range of armour and other vulnerability reduction measures which are currently being developed. The wide range of material and structural solutions to mitigate the damage from weapons effects is a result of the wide range of platforms, environmental conditions and threats being defeated. The appropriate development and selection of these solutions highlights the need for well trained technologists in the terminal effects field.

This report also reinforces the development of the Defence Materials Technology Centre (DMTC) in 2008 to provide the basic knowledge in the area of materials development for armour applications. It is essential that DSTO continues to align the focus of materials development with the current environmental and threat conditions within which the ADF operates. This is further strengthened by DSTO's domestic and international interactions under cooperative agreements.

The link between the development of simulation and modelling tools and the development of vulnerability reduction measures must be maintained, along with a fundamental understanding of the physical processes involved, in order to accurately predict potential battle damage. This report also highlights the following important areas of study:

6.1 Lightweight Armour and Appliqué Armour Solutions

Development of lightweight armour and appliqué armour solutions to defeat a range of weapons. Both land and maritime platforms have tight weight and cost constraints.

6.2 Explosion Resistant Coatings (ERC)

Continued development and understanding of the protective properties of new materials such as explosion resistant coatings (ERC). Platform manufacturers are currently offering ERC materials to various projects, however the basic performance parameters of existing materials are not known, nor are these materials optimised.

6.3 Transparent Armour

Development of much lighter, long life transparent armour which is able to defeat a range of fragmenting and penetrator threats, together with appropriate optical and non-ballistic properties such as environmental durability.

6.4 Synergistic Effects of the Blast and Fragment

Creation of a collaborative program in DSTO to study the synergic effects of blast and fragmentation on a platform. The majority of improvised explosive device incidents are from near-field detonations involving both blast and fragment effects. Although the physical processes of explosive detonations have been well characterised, the complex interaction of these effects on platforms, particularly in the near field, is difficult to simulate and also difficult to protect against.

6.5 Underwater Explosive Effects and Associated Damage

As part of the current MPD long range research program investigating underwater explosive effects and associated damage for both submerged and floating naval vessels, there are a number of additional research areas that could be included. These are the study of shock transmission through pipes and the propagation of shock through tanks associated with ships and submarines; compliant coatings, to reduce shock transmission through wetted surfaces; and semi-active equipment shock isolation mounts.

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Appendix A: Codes

A.1. ConWep

ConWep is a collection of conventional weapons effects calculations from the equations and curves of TM 5-855-1, "Design and Analysis of Hardened Structures to Conventional Weapons Effects" [45]. The software calculates a range of blast effects from different types of high explosives and weapons, including blast loads, fragment penetration depths into concrete and steel, concrete wall breaching, projectile penetration into rock and soil, cratering and ground shock. Airblast calculations include free-field and reflected blast pressure histories from free-air and surface burst explosions; average peak pressure and impulse from a hemispherical surface burst on a specified reflected wall area; peak pressure from buried explosions; blast pressure in tunnels; and quasistatic pressure histories from vented internal explosions.

A.2. BLASTX

BLASTX is a computer program that calculates internal blast pressure histories in single and multi-room buildings, considering a wide range of building geometries. The calculated blast pressure histories include reflections off adjacent surfaces, shock propagation from adjacent rooms, blast wave shadowing around corners and quasistatic blast pressure. The user can specify openings in walls allowing shock and quasistatic pressure to propagate between rooms, which can open only after specified failure criteria are satisfied. BLASTX is based on semi-empirical methods, including nonlinear additive laws for blast pressures from multiple reflecting surfaces based on computational fluid dynamics. BLASTX has wide ranging capabilities for calculating blast loads for many different high explosive charge and room geometries, but it is not validated for all of these cases.

A.3. BEEM

BEEM is a Windows-based program created to assist Engineers, Technicians, and Security Personnel in the performance of damage assessments to buildings and people. It is a wholly owned U.S. government program, and is a collaborative development effort of the U.S. Army Corps of Engineers, Engineering Research and Development Center, Waterways Experiment Station (ERDC-GSL), Protective Design Center (CENWO-ED-S), and Naval Surface Warfare Center, Dahlgren Division (NSWC / DD). BEEM models the effects of various types of explosive devices and shows the degree of damage to personnel and buildings nearby.

BEEM is based on simplified engineering models that allow for quick analysis of several different explosive threat scenarios. Current uses include calculating blast loads for incident and reflected pressures from ground-level hemispherical bursts; estimating blast damage of structural elements and predicting hazards to personnel from window glass; and predicting human injury from air blast. Applications of this program include:

- Assessing threats to facilities
- Use as a design tool for retrofit of buildings
- Performing vulnerability assessments
- Investigation of bombing events

- Force protection planning
- Access control point planning
- Base camp design
- Planning sites for new construction.

BEEM displays its results in an interactive 3D graphical environment and in eXtensible Markup Language (XML) data format. This generated output is suitable for inclusion into a report or presentation of the resulting blast analysis.

A.4. SHOCK

SHOCK is computer program that calculates the average peak pressure and impulse from an internal explosion on a user selected area of the wall of rectangular room. The impulse from reflections off adjacent room surfaces is linearly added. This program is older and more simplified than BLASTX, however it has the advantage that it can average the impulse and peak pressure over many points of a user selected wall area, whereas BLASTX only averages the blast pressure history over a few user defined points. SHOCK is based on blast load prediction curves from TM 5-1300 "Structures to Resist the Effects of Accidental Explosions." [58]

A.5. FATEPEN

FATEPEN [46] (Fast Air Target Encounter PENetration) is a set of fast running algorithms that simulate the penetration of spaced target structures by fragments, long rods, and projectiles impacting at speeds up to about 5 km / sec. It was developed for the Naval Surface Warfare Center, Dahlgren Division (NSWC / DD) by Applied Research Associates, Inc., (ARA). The development of FATEPEN is currently being supported by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG / ME) and the Lethality and Weapons Effectiveness Branch of NSWC / DD.

The model predicts penetrator mass loss, velocity loss, trajectory change, and tumbling throughout a target. The mass loss model includes impact fracture calculations that may transform an incident warhead fragment into a post-impact expanding, multi-particle debris cloud which FATEPEN then tracks through the remaining target structure.

A.6. THOR

The empirically derived Thor equations relate fragmentation parameters to the penetration of metallic and non-metallic target materials [47].

A.7. LSDYNA

LS-DYNA is a general-purpose transient dynamic finite element program capable of simulating complex real-world problems involving large deformations. LS-DYNA is the industry standard for analysing structures subjected to short duration loads and significant geometric nonlinearities. Capabilities include fully Eulerian simulations, (ALE), coupled Lagrangian-Eulerian and Smoothed Particle Hydrodynamics (SPH). An extensive library of material models is available.

A.8. CTH

The CTH suite of computer codes is designed to treat a wide range of shock wave propagation and material motions. Finite-volume analogs of the Lagrangian equations of momentum and energy conservation are employed with continuous rezoning to construct Eulerian differencing. CTH has models suitable for most conditions encountered in shock physics including material strength, fracture, distended materials, high explosives, and a variety of boundary conditions. The material equation-of-state models allow description of most states of matter normally encountered in shock physics. CTH is used for studying weapon effects, armor / anti-armor interactions, warhead design, high-explosive initiation physics, and weapon safety issues.

A.9. SAP2000

SAP2000 [51], is a structural software package. Its advanced analytical techniques allow for step-by-step large deformation analysis, multiple p-delta, and eigen and ritz modal analyses. Design options include fully interactive and graphical steel, concrete, and aluminium frame member design for static and dynamic loads including material and geometrical non-linearity. SAP2000 can be used in the progressive collapse analysis and design of buildings using the alternate path method. Other applications include structural analysis, design of test frames to support blast tests and focused structural analysis of critical building components.

A.10. AUTODYN

AUTODYN is an explicit software package for non-linear dynamics. It incorporates finite element analysis, computational fluid dynamics, a mesh-free SPH capability and coupling between these techniques and material physics. This means that instead of applying the same general solver to all regions, a solver optimised for a particular dynamic or material response may be used for each individual region [59]. For example, AUTODYN has been used within DSTO to model air blast using an Eulerian solver, coupled with a polymer coated plate using a Lagrangian solver [32].

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19. ABSTRACT
This report provides a literature review of the area of battle damage prediction and vulnerability reduction methods in the land and maritime domains and will provide input into the strategic planning process for Maritime Platforms Division's (MPD) long range research program.